

# Diphoton Signatures from Heavy Axion Decays at the CERN Large Hadron Collider

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Recently, the LHC collaborations, ATLAS and CMS, have announced an excess in the diphoton channel with local significance of about  $3\sigma$  around an invariant mass distribution of  $\sim 750$  GeV, after analyzing new data collected at centre-of-mass energies of  $\sqrt{s} = 13$  TeV. We present a possible physical interpretation of such a signature, within the framework of a minimal UV-complete model with a massive singlet pseudo-scalar state  $a$  that couples to a new TeV-scale coloured vector-like fermion  $F$ , whose hypercharge quantum number is a non-zero integer. The pseudo-scalar state  $a$  might be a heavy pseudo-Goldstone boson, such as a heavy axion, which decays into two photons and whose mass lies around the excess region. The mass of the CP-odd state  $a$  and its coupling to  $F$  may be due to non-perturbative effects, which can break the original Goldstone shift symmetry dynamically. The possible role that the heavy axion  $a$  can play in the radiative generation of a seesaw Majorana scale and in the solution to the so-called strong CP problem is briefly discussed.

KEYWORDS: Diboson signals; Heavy Axions; Vector-like Fermions

Recently, the ATLAS and CMS collaborations have analyzed Run 2 LHC data gathered at centre-of-mass energies of  $\sqrt{s} = 13$  TeV. They reported an excess in the diphoton channel around an invariant mass distribution of  $\sim 750$  GeV, with local significance of  $3.6\sigma$  and  $2.6\sigma$  confidence level (CL), respectively [1]. Interestingly enough, Run 2 data do not show up any significant excess in other diboson channels, such as  $ZZ$ ,  $W^+W^-$  and  $Z\gamma$ , whilst the Run-1 bumps seen around the 2 TeV region have now become almost statistically insignificant.

In this short note, we offer a possible interpretation of such an excess in the diphoton channel, within the framework of a minimal UV-complete model with a massive singlet pseudo-scalar state  $a$  that couples to new coloured vector-like fermions  $F_{L,R}$ . These vector-like fermions are very heavy with masses  $m_F \gtrsim 1.5$  TeV, so as to have escaped detection so far at the LHC. They are charged under the  $SU(3)_C$  group of Quantum Chromodynamics (QCD), but they are singlets under the weak  $SU(2)_L$  group of the Standard Model (SM). They must also have non-zero integer hypercharges, e.g.  $Y_{F_L} = Y_{F_R} = 1, 2, \dots$ , which forbid them to have Yukawa interactions with the SM quarks. On the other hand, the pseudo-scalar state  $a$  may well be a heavy pseudo-Goldstone boson, such as a heavy axion, which decays into two photons with a mass that lies around the excess region of  $\sim 750$  GeV. Both the mass  $M_a$  of the state  $a$  and its CP-odd coupling to the Dirac vector-like fermion  $F$ ,  $h_F \bar{F} i \gamma_5 F$ , could originate from non-perturbative effects that break the original axion shift symmetry.

The minimal UV-complete model that we will be considering here is related to the one that discussed earlier in Ref. [2]. The relevant non-SM part of the Lagrangian of interest to us is given by

$$\mathcal{L} = \bar{F} (i \not{D} - m_F) F + \frac{1}{2} (\partial_\mu a) (\partial^\mu a) - \frac{1}{2} M_a^2 a^2 - h_F a \bar{F} i \gamma_5 F. \quad (1)$$

In the above,  $D_\mu = \partial_\mu + ig_s T^a G_\mu^a + ig' (Y_F/2) B_\mu$  is the covariant derivative acting on the exotic coloured Dirac fermion  $F$ , where  $G_\mu^a$  and  $B_\mu$  are the  $SU(3)_C$  and  $U(1)_Y$  gauge bosons, respectively, and  $T^a$  (with  $a = 1, 2, \dots, 8$ ) are the generators of the  $SU(3)_C$  gauge group. Notice that Lagrangian (1) is invariant under the CP transformations:  $a(t, \mathbf{x}) \rightarrow -a(t, -\mathbf{x})$  and  $\bar{F}(t, \mathbf{x}) i \gamma_5 F(t, \mathbf{x}) \rightarrow -\bar{F}(t, -\mathbf{x}) i \gamma_5 F(t, -\mathbf{x})$ . In the absence of the fermion mass term  $m_F \bar{F} F$ , Lagrangian (1) is also invariant under the chirality discrete transformations:  $a \rightarrow -a$  and  $F_{R(L)} \rightarrow +(-) F_{R(L)}$ . Given that  $m_F \neq 0$ , this latter symmetry is broken softly by the dimension-3 mass operator  $m_F \bar{F} F$ . Finally, it is important to remark that the squared mass  $M_a^2$  and the Yukawa couplings  $h_F$  in Lagrangian (1) break explicitly the Goldstone shift symmetry:  $a \rightarrow a + c$ , where  $c$  is an arbitrary constant. The possible origin of such a breaking could be due to non-perturbative effects related to some unspecified strong dynamics.

In the above minimal extension of the SM, the pseudoscalar field  $a$  couples to the electromagnetic (em) field  $A_\mu$  and the gluon fields  $G_\mu^a$ , via the five-dimensional operators:  $a F^{\mu\nu} \tilde{F}_{\mu\nu}$  and  $a G^{a\mu\nu} \tilde{G}_{\mu\nu}^a$ , where  $F^{\mu\nu}$  and  $G^{a,\mu\nu}$  are the  $U(1)_{\text{em}}$  and  $SU(3)_C$  field strength tensors, respectively, and  $\tilde{F}_{\mu\nu} \equiv \frac{1}{2} \varepsilon_{\mu\nu\lambda\rho} F^{\lambda\rho}$  and  $\tilde{G}_{\mu\nu}^a \equiv \frac{1}{2} \varepsilon_{\mu\nu\lambda\rho} G^{a,\lambda\rho}$  are their

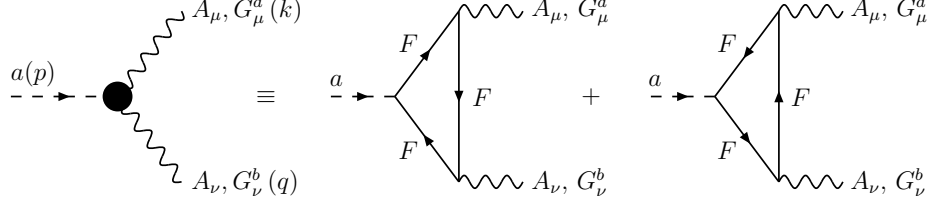


FIG. 1: The operators  $aF_{\mu\nu}\tilde{F}^{\mu\nu}$  and  $aG_{\mu\nu}^a\tilde{G}_{\mu\nu}^a$ , as induced by the chiral global anomaly of the heavy fermion  $F$ , with the convention  $p + k + q = 0$ .

corresponding dual tensors. These operators are induced by the chiral global anomalies of the heavy fermion  $F$ , through the triangle graphs shown in Fig. 1. With the convention that all momenta are incoming, i.e.  $p + k + q = 0$ , the one-loop  $a(p)$ - $A_\mu(k)$ - $A_\nu(q)$  coupling reads [3–5]:

$$i\Gamma_{\mu\nu}^{aAA}(p, k, q) = iQ_F^2 \frac{N_C \alpha_{\text{em}}}{\pi} \frac{h_F}{m_F} F_P\left(\frac{p^2}{4m_F^2}\right) \varepsilon_{\mu\nu\lambda\rho} k^\lambda q^\rho, \quad (2)$$

where  $Q_F = Y_F/2$  is the electric charge of the heavy fermion  $F$ ,  $N_C = 3$  is its colour degrees of freedom,  $\alpha_{\text{em}} = e^2/(4\pi)$  is the electromagnetic fine structure constant, and  $\varepsilon_{\mu\nu\lambda\rho}$  is the usual anti-symmetric Levi-Civita tensor (with the convention:  $\varepsilon^{0123} = +1$ ). Moreover, the loop function  $F_P(\tau)$  was calculated long time ago [3] and found to be:

$$F_P(\tau) = \begin{cases} \frac{1}{\tau} \arcsin^2 \sqrt{\tau}; & |\tau| \leq 1, \\ -\frac{1}{4\tau} \left[ \ln \left( \frac{\sqrt{\tau} + \sqrt{\tau-1}}{\sqrt{\tau} - \sqrt{\tau-1}} \right) - i\pi \right]^2; & |\tau| \geq 1. \end{cases} \quad (3)$$

Note that for  $|\tau| \ll 1$ , we have  $F_P(\tau) = 1 + \tau/3 + \mathcal{O}(\tau^2)$ , whereas for  $|\tau| \gg 1$ ,  $F_P(\tau) \rightarrow -\ln^2 |\tau|/(4\tau)$  which goes to zero asymptotically as  $\tau \rightarrow \infty$ .

By analogy, the  $\text{SU}(3)_C$  global anomaly generates an effective interaction of the heavy axion  $a$  to gluons  $G_\mu^a$ , as shown in Fig. 1. The effective  $a(p)$ - $G_\mu^a(k)$ - $G_\nu^b(q)$  coupling is given by

$$i\Gamma_{\mu\nu}^{aG^aG^b}(p, k, q) = i\delta^{ab} \frac{\alpha_s}{2\pi} \frac{h_F}{m_F} F_P\left(\frac{p^2}{4m_F^2}\right) \varepsilon_{\mu\nu\lambda\rho} k^\lambda q^\rho, \quad (4)$$

where  $\alpha_s = g_s^2/(4\pi)$  is the strong fine structure constant.

With the aid of the effective couplings given in (2) and (4), it is straightforward to calculate the decay widths of the heavy axion  $a$  into photons ( $\gamma$ ) and gluons ( $g$ ):

$$\Gamma(a \rightarrow \gamma\gamma) = \frac{N_C^2 \alpha_{\text{em}}^2}{64\pi^3} Q_F^4 h_F^2 \frac{M_a^3}{m_F^2} |F_P(\tau_a)|^2, \quad (5)$$

$$\Gamma(a \rightarrow gg) = \frac{\alpha_s^2}{32\pi^3} h_F^2 \frac{M_a^3}{m_F^2} |F_P(\tau_a)|^2 K_a^g, \quad (6)$$

where  $\tau_a \equiv M_a^2/(4m_F^2)$  and  $K_a^g \approx 1.6$  is a QCD loop enhancement factor which includes the leading order QCD corrections [6]. In addition, the other diboson decay channels, such as  $a \rightarrow ZZ$ ,  $Z\gamma$  and  $W^+W^-$ , may be reliably estimated to leading order in  $M_Z^2/M_a^2$  [7] as follows:

$$\frac{\Gamma(a \rightarrow ZZ)}{\Gamma(a \rightarrow \gamma\gamma)} \approx \frac{\sin^4 \theta_w}{\cos^4 \theta_w} \approx 0.082, \quad \frac{\Gamma(a \rightarrow Z\gamma)}{\Gamma(a \rightarrow \gamma\gamma)} \approx \frac{2 \sin^2 \theta_w}{\cos^2 \theta_w} \approx 0.57, \quad (7)$$

whilst the decay width  $a \rightarrow W^+W^-$  is negligible, since the corresponding  $aW^+W^-$  effective coupling is generated at the two-loop level, e.g. from the one-loop induced  $a\gamma\gamma$  coupling. To satisfy the LHC constraints on the masses of exotic coloured fermions, we may assume that the vector-like fermion  $F$  is heavier than  $a$ , e.g.  $m_F \gtrsim 1.5$  TeV, in which case  $\tau_a \ll 1$ . Hence, the loop function  $F_P(\tau_a)$  may well be approximated as  $F_P(\tau_a) \approx 1$ .

If we now take the ratio  $R$  of the photonic versus the gluonic decay width given in (5) and (6), we readily find that

$$R \equiv \frac{\Gamma(a \rightarrow \gamma\gamma)}{\Gamma(a \rightarrow gg)} = \frac{N_C^2 \alpha_{\text{em}}^2 Q_F^4}{2 \alpha_s^2 K_a^g}. \quad (8)$$

Observe that the ratio  $R$  is independent of the Yukawa coupling  $h_F$  and, for  $Q_F \geq 2$ , we obtain  $R > 1$  and the decay  $a \rightarrow \gamma\gamma$  can easily become the dominant mode.

The production cross section of heavy axions via gluon-gluon fusion [8] may be calculated as follows:

$$\sigma(pp \rightarrow a \rightarrow \gamma\gamma) \approx \sigma(pp \rightarrow a) B(a \rightarrow \gamma\gamma), \quad (9)$$

where  $B(a \rightarrow \gamma\gamma) \approx R/(1 + 1.57R)$  is the branching fraction for the decay channel  $a \rightarrow \gamma\gamma$ , with  $R$  given in (8). For centre-of-mass energies of  $\sqrt{s} = 13$  TeV, we may naively estimate the cross section  $\sigma(pp \rightarrow a)$  as

$$\sigma(pp \rightarrow a) \sim \sigma_{\text{SM}}(pp \rightarrow H) \times h_F^2 \frac{m_t^2}{m_F^2} \frac{M_a^2}{M_H^2}, \quad (10)$$

where  $\sigma_{\text{SM}}(pp \rightarrow H) \approx 40$  pb is a reference production cross section of the SM Higgs boson  $H$  via gluon-gluon fusion, with  $M_H \approx 125$  GeV [9]. Hence, for  $M_a = 750$  GeV (or  $M_a/M_H = 6$ ),  $m_F/m_t = 10$  and  $h_F = 0.1$ , we find that

$$\sigma(pp \rightarrow a \rightarrow \gamma\gamma) \sim 15 \text{ fb} \times B(a \rightarrow \gamma\gamma). \quad (11)$$

For  $B(a \rightarrow \gamma\gamma) \sim 1$  and an integrated luminosity  $\mathcal{L} = 3 \text{ fb}^{-1}$  at  $\sqrt{s} = 13$  TeV, we obtain about 45 signal events, which is compatible with the diphoton-excess events reported in [1].

As discussed in detail in [2], axion-like fields could act as mediators to generate TeV-scale gauge-invariant masses, such as  $m_F \bar{F}F$ , for vector-like fermions through global anomalies at the three-loop level. In particular, a gauge-invariant Majorana mass term  $m_M (\bar{\nu}_R)^C \nu_R$  can be generated [10], if heavy axion fields couple to Kalb–Ramond axions [11, 12] that occur in torsionful theories of Quantum Gravity. Light axions play an important role in solving the strong CP problem via the so-called Peccei–Quinn mechanism [13–16]. Thus, the possible presence of a heavy axion, or a multitude of axions [17, 18], may give rise to interesting mixing phenomena and possibly to new effects in astrophysical considerations [19].

In conclusion, we have presented a minimal UV-complete model, based on the possible existence of a heavy axion with mass  $M_a \approx 750$  GeV, which could offer a possible physical interpretation of the diphoton excess observed in the Run 2 data. The model requires the presence of a new TeV-scale coloured vector-like fermion  $F$ , which has a non-zero integer hypercharge. For large electric charges  $Q_F \geq 2$ , the photonic decay mode  $a \rightarrow \gamma\gamma$  becomes naturally the dominant channel. The latter, along with the branching fractions given in (7), provide a unique prediction of our minimal model that can be tested with future Run 2 data. Nevertheless, our model may require an extension to its field content, as it exhibits a Landau pole at energy scales  $Q \lesssim 10^{14}$  GeV, for  $Q_F \geq 2$ . Further studies are therefore needed, so as to be able to fully assess the physical significance of the observed diphoton excess, as a firm signature of New Physics at the LHC.

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ATLAS results (Speaker: Marumi Kado), based on the ATLAS Note, ATLAS-CONF-2015-081.
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